National Aeronautics and Space Administration

High-Fidelity Analysis of a Boundary Layer Ingesting Fan

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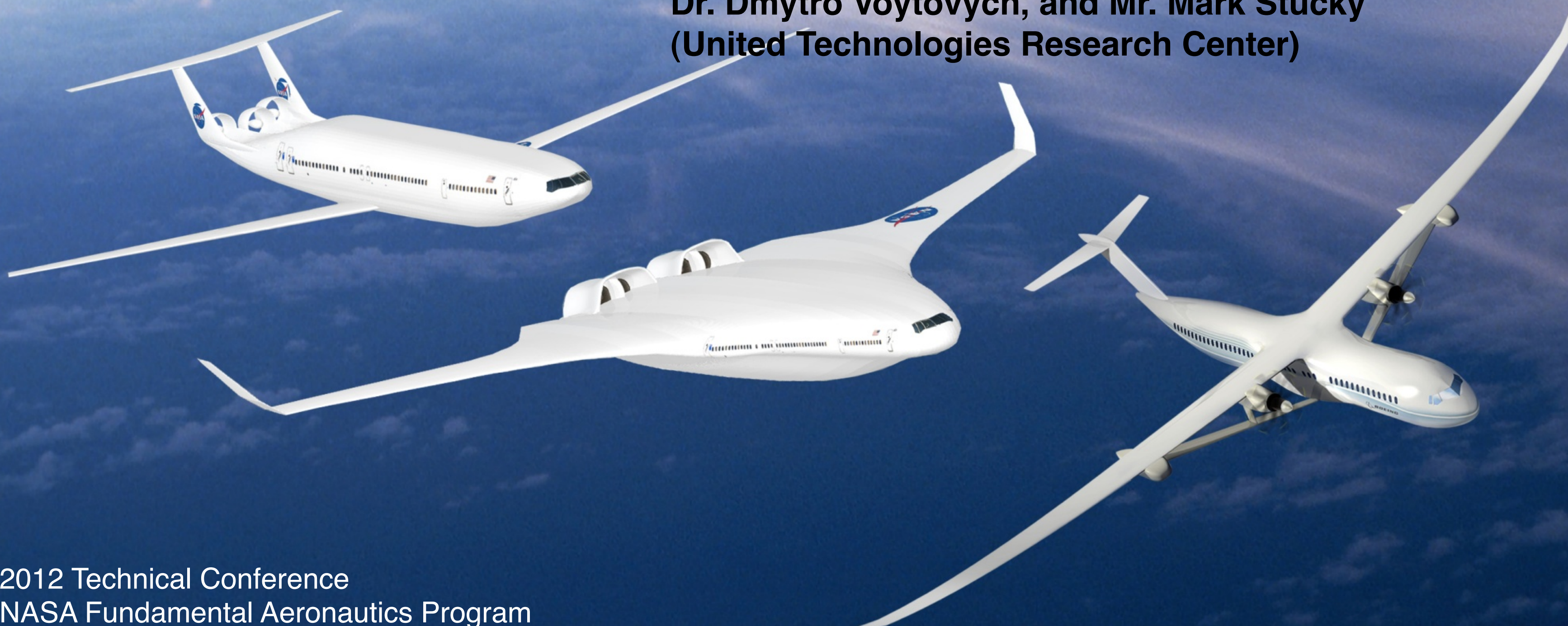

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Outline

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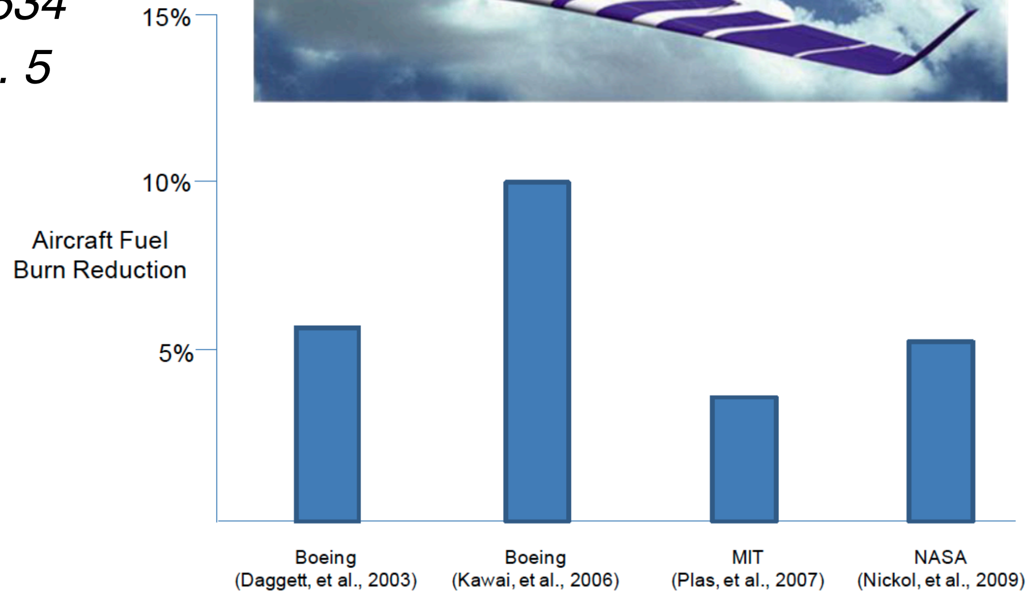
- Goals and Objectives
- Fan CFD Analysis – TURBO-AE Code
- Fan Performance – Clean Inflow, Distorted Inflow
- Aeroelastic Formulation
- Structural Dynamics
- Inlet Distortion Forced Response, Dynamic Stress
- Blade Vibrations – Flutter Stability
  - Clean Inflow
  - Distorted Inflow
- Summary and Future Work

Background

- Boundary Layer Ingestion (BLI) Propulsion has the potential for significant reduction in Aircraft Fuel Burn (5-10%)
- Previous studies referenced in 2011 FAP presentation by Razvan Florea:

Bangert, et al., NASA-CR-3743 (1983)
Daggett, et al., NASA-CR-2003-212670
Berrier, NASA-TP-2005-213766
Campbell, AIAA 2005-0459
Kawai, et al., NASA-CR-2006-214534
Carter, AIAA JOA 2006, Vol 43, No. 5
Plas, MIT PhD Thesis 2006
Plas, et al., AIAA 2007-450
Kawai, NASA-CR-2008-215141
Nikol, NASA-TM-2008-215112
Drela, AIAA 2009-3762
Nikol, McCuller, AIAA 2009-931

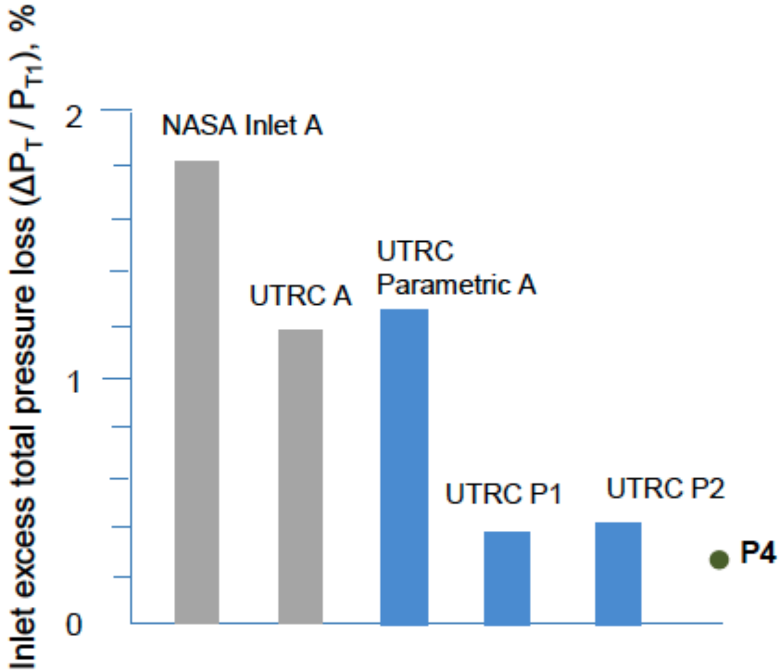


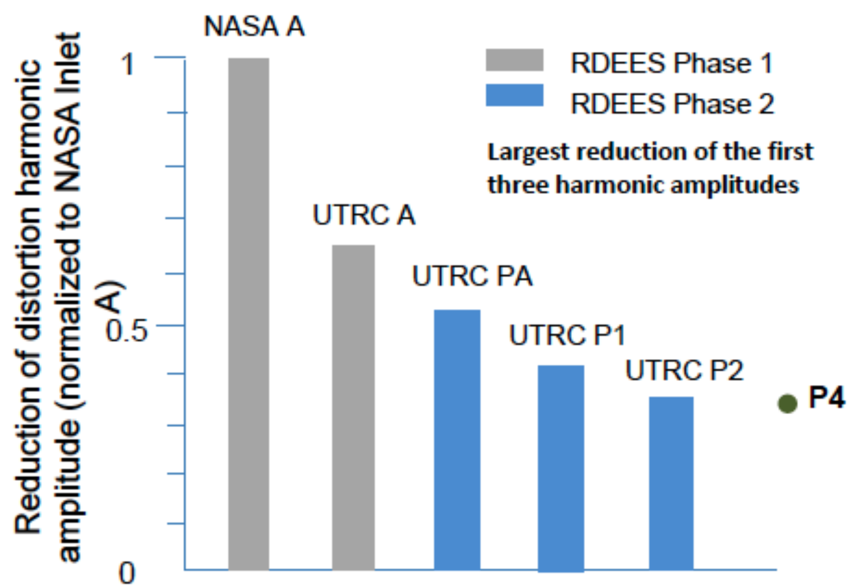
Technical Challenges

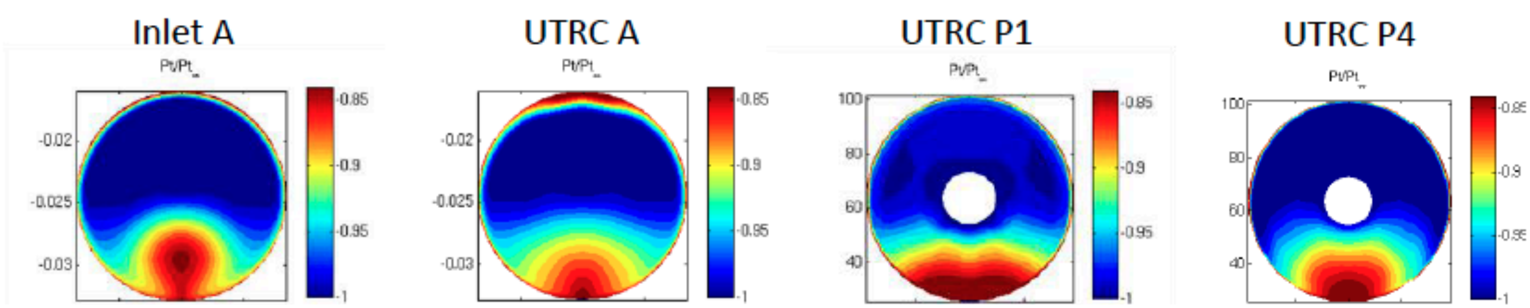
- The potential benefits of Boundary Layer Ingestion (BLI) Propulsion can be diminished by considerations of
  - Inlet total pressure loss
  - Fan efficiency reduction
  - Fan stall margin reduction
  - Fan aeromechanics (dynamic stresses and flutter stability)

Optimization-Based Parametric Inlet Design

- *Inlet excess pressure loss reduced ~4-5x relative to original Inlet A starting point*
- *Dominant distortion harmonic amplitudes reduced ~30-50% relative to original Inlet A starting point*





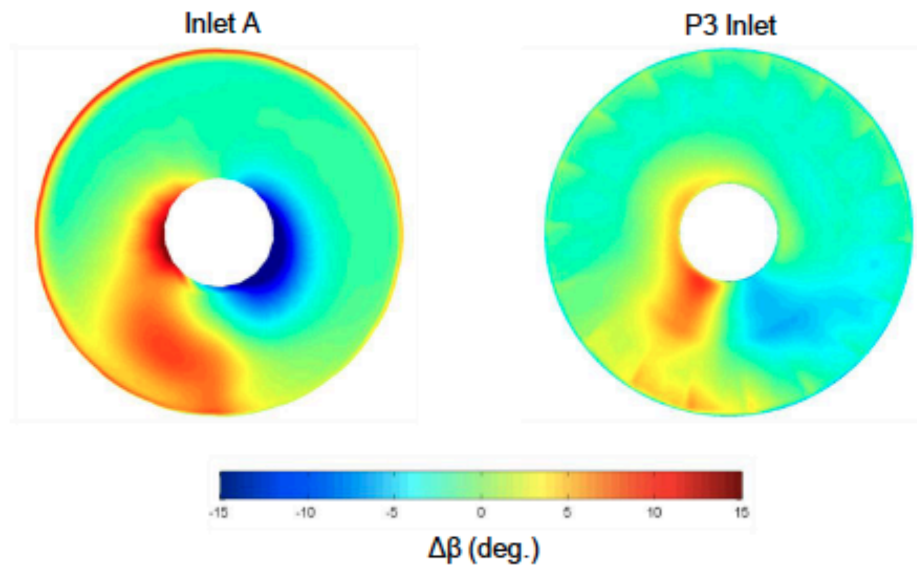


Aerodynamic Interface Plane (AIP) total pressure contours

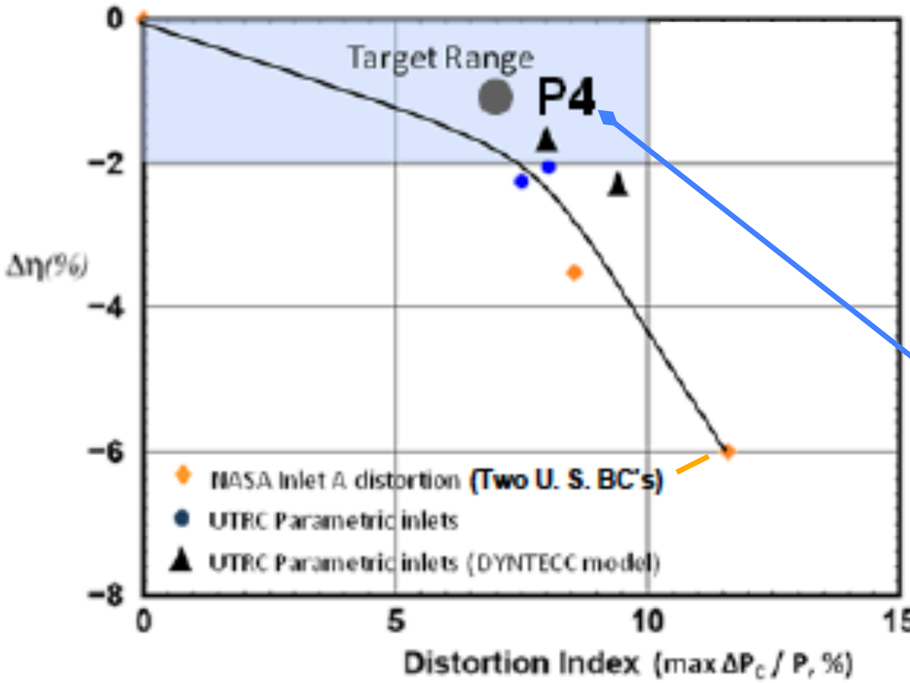
Fan Efficiency with Distortion-Optimized Inlet

Inlet significantly improves fan interaction with incoming distortion

Excursions in Fan Blade Leading Edge Relative Incidence from Clean Inflow



Fan Efficiency Reduction (%)



Inlet enables fan to meet performance target

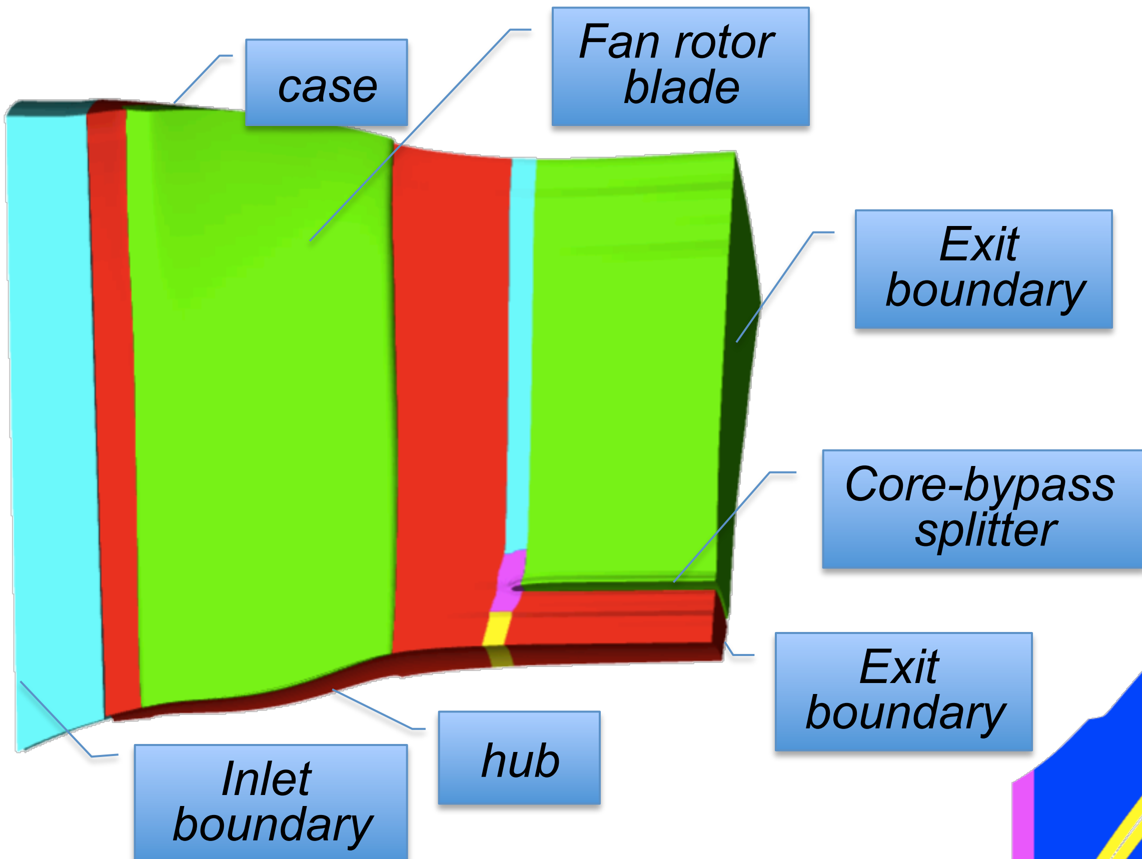
Fan CFD Analysis – TURBO Code

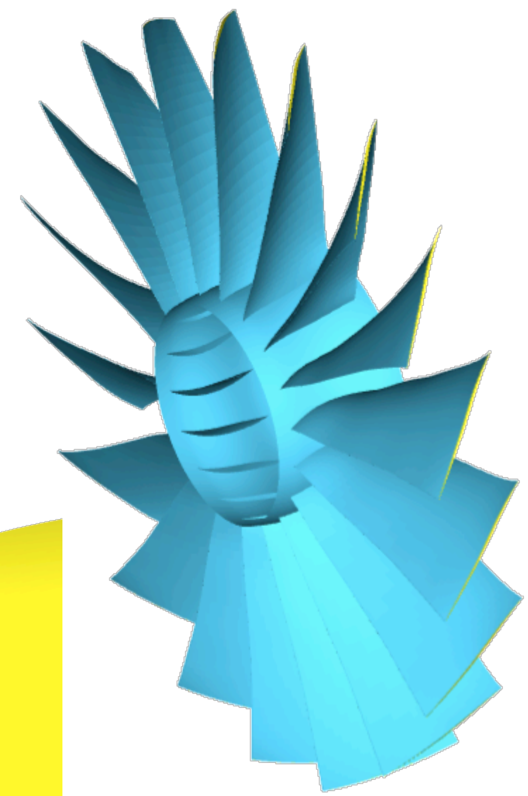
- Implicit, finite-volume solver
- Reynolds-Averaged Navier Stokes equations
- Structured multi-block code
- Multi blade-row code
- k-epsilon turbulence model
- Inlet distortion boundary condition
- Throttle exit boundary condition

- Dynamic grid deformation for blade vibration
- Prescribed harmonic blade vibrations with energy method to evaluate flutter stability

Fan Computational Domain

- Analysis of an Aero Design Iteration (not the Final Design)

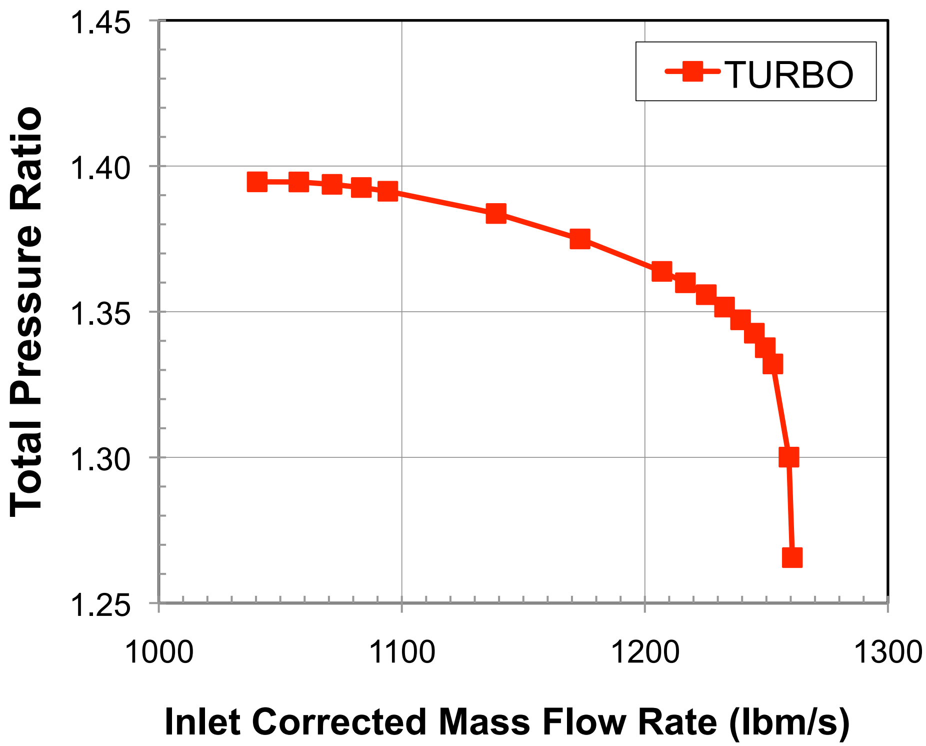


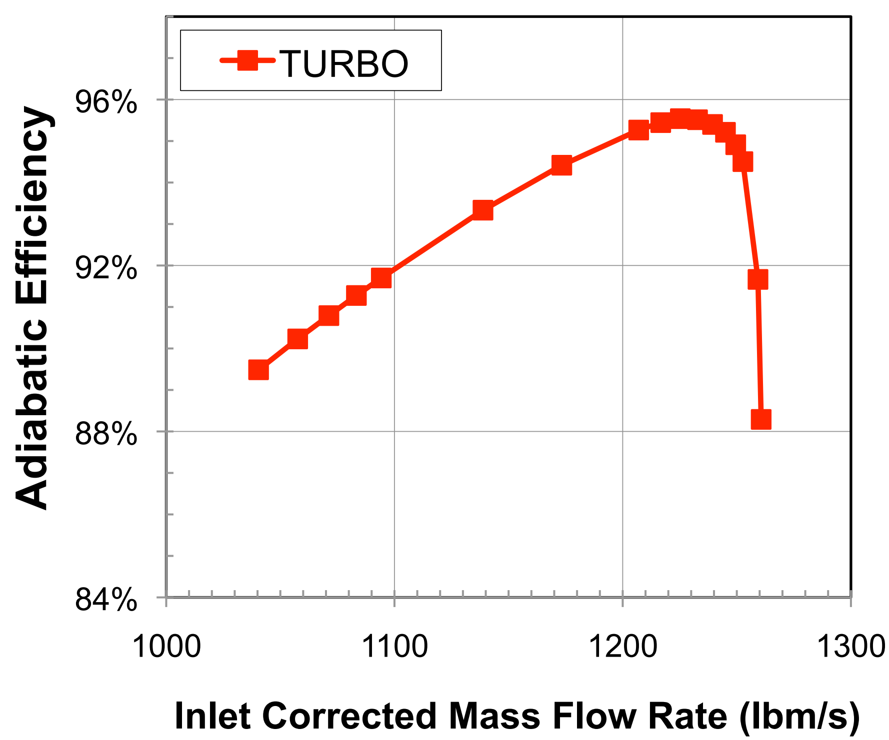


- H, O, and C blocks of mesh generated by UTRC

Fan Performance – Clean Inflow

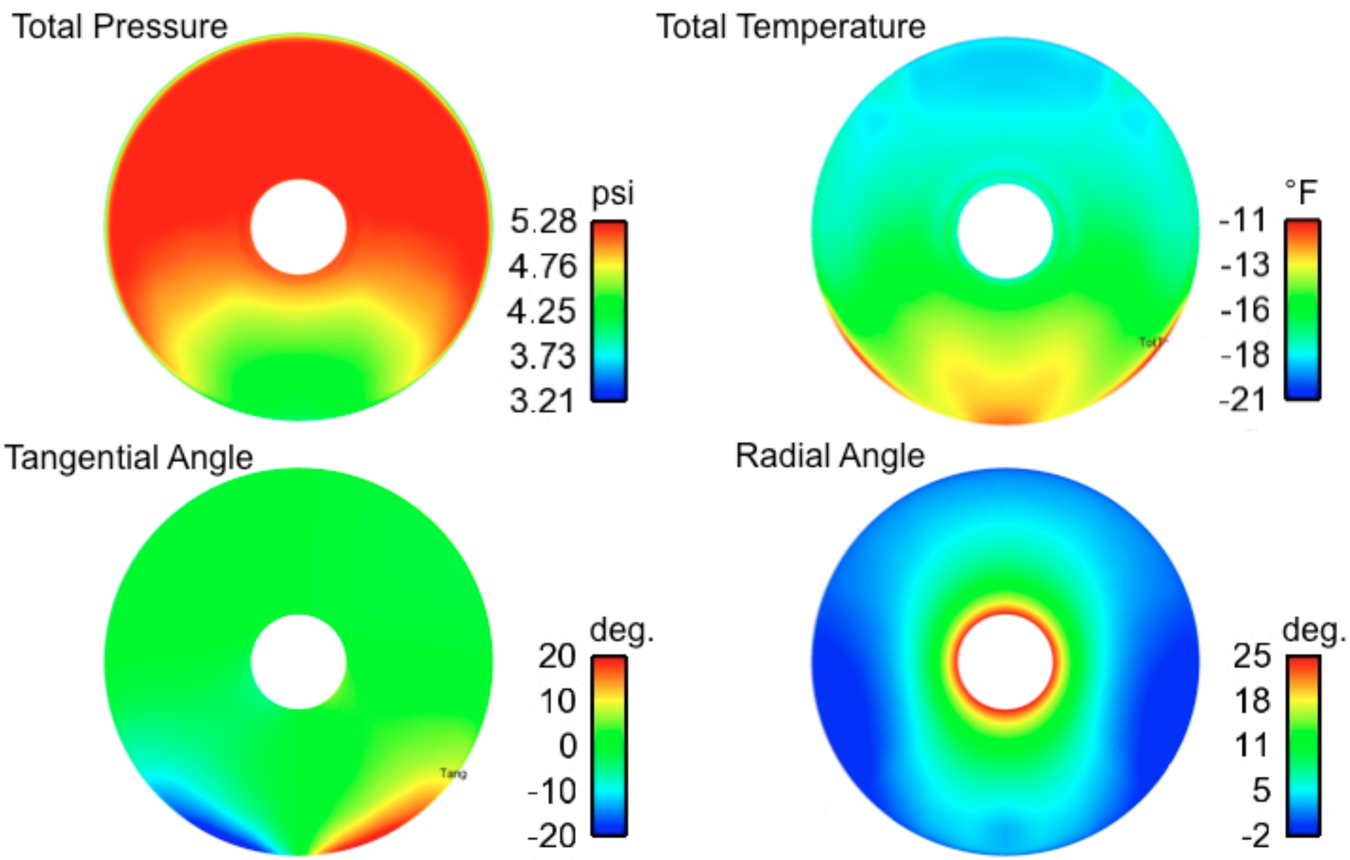
- TURBO code (RANS solver) used with radial inlet profile of total pressure, total temperature, and flow angles
- Speedline traversed by setting exit throttle condition and converging flow solutions





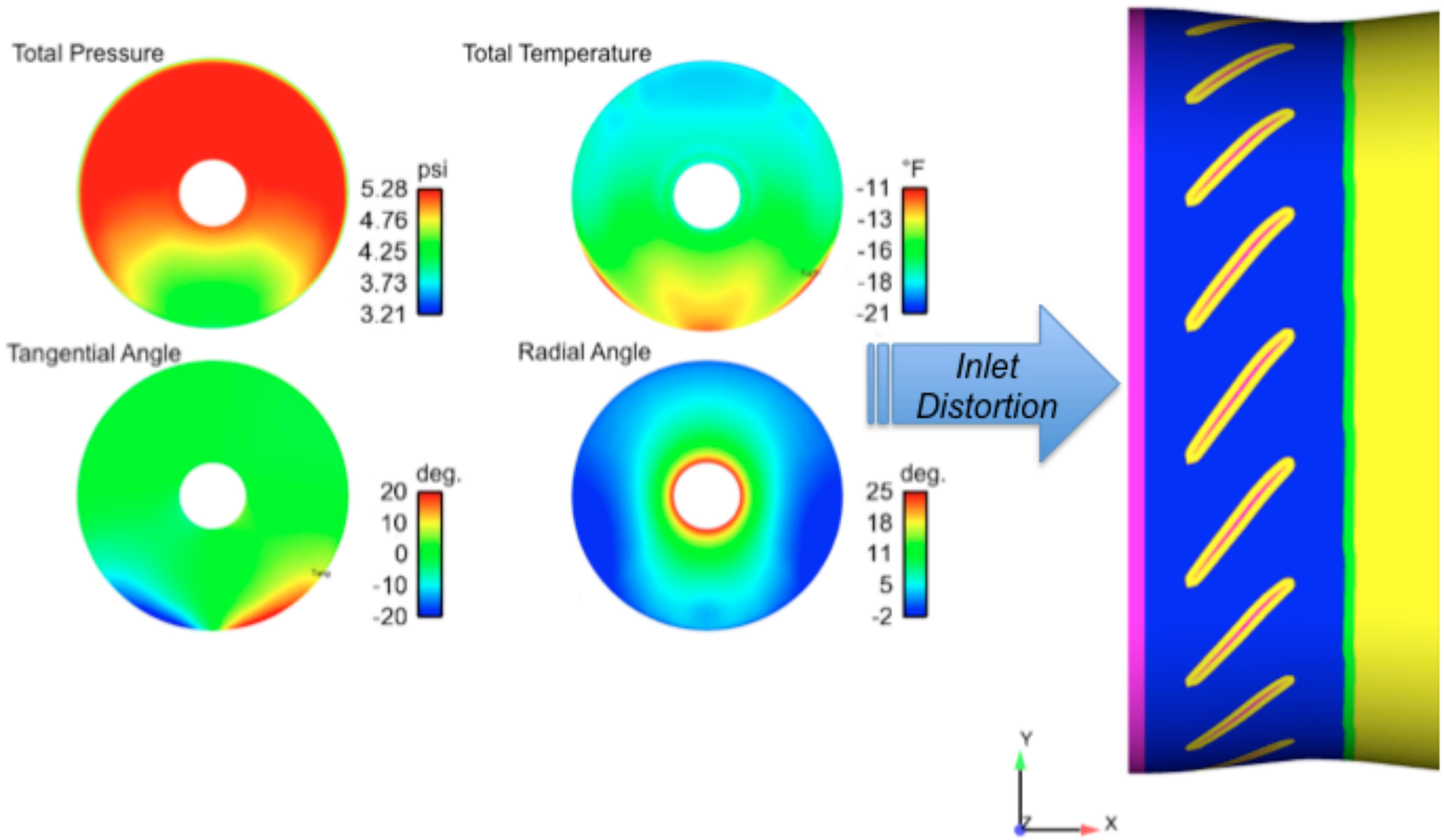
Inlet Flowfield Provides Distortion Pattern

- Inlet flow computations were performed at UTRC for an inlet design iteration (not final design) and the flowfield results were provided to NASA



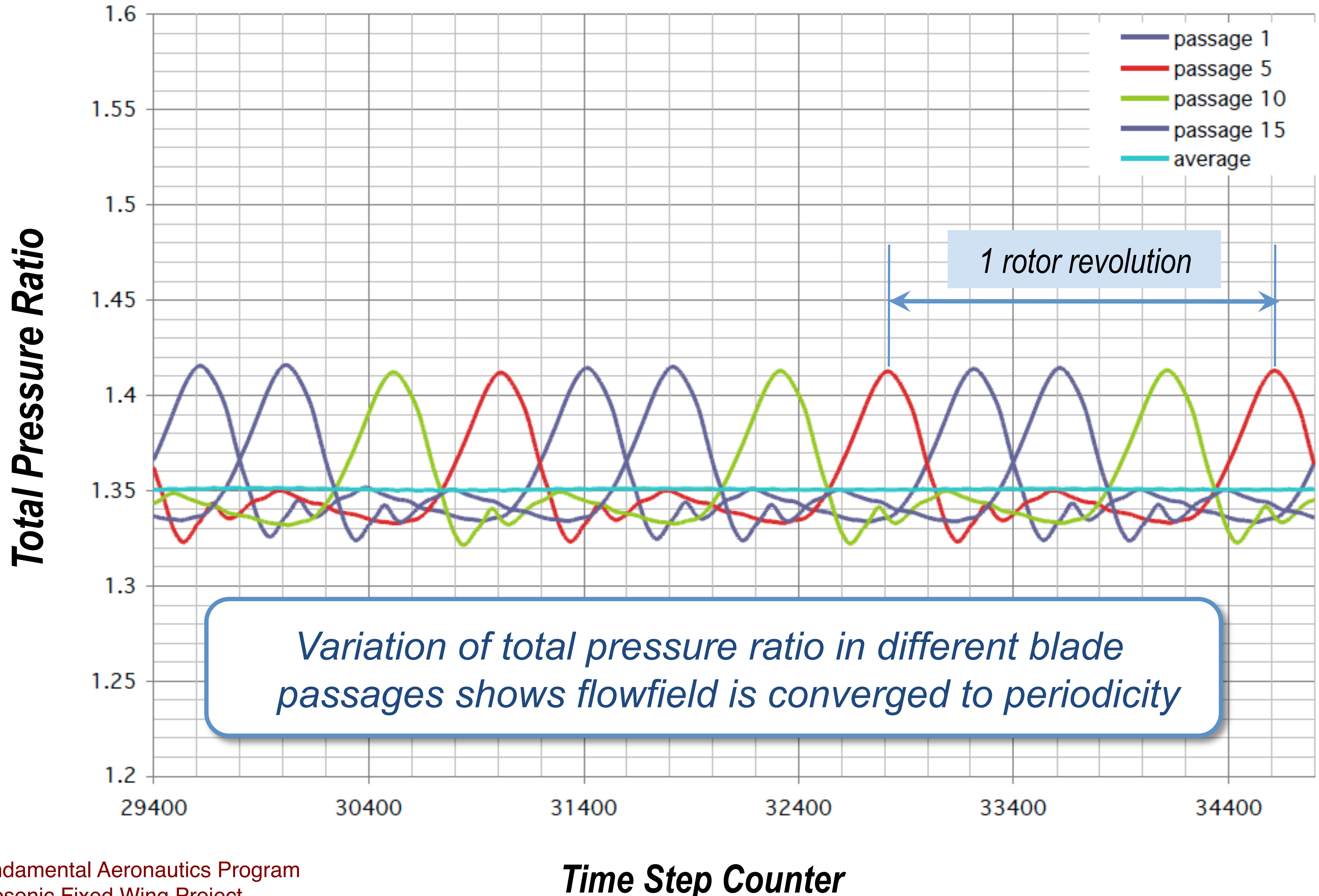
Fan Computation with Inlet Distortion

- Inlet distortion is prescribed as boundary condition at inlet boundary of the fan computational domain (18-blade fan rotor and splitter)



Periodicity of Flowfield Around the Rotor

- Total pressure ratio for various blade passages



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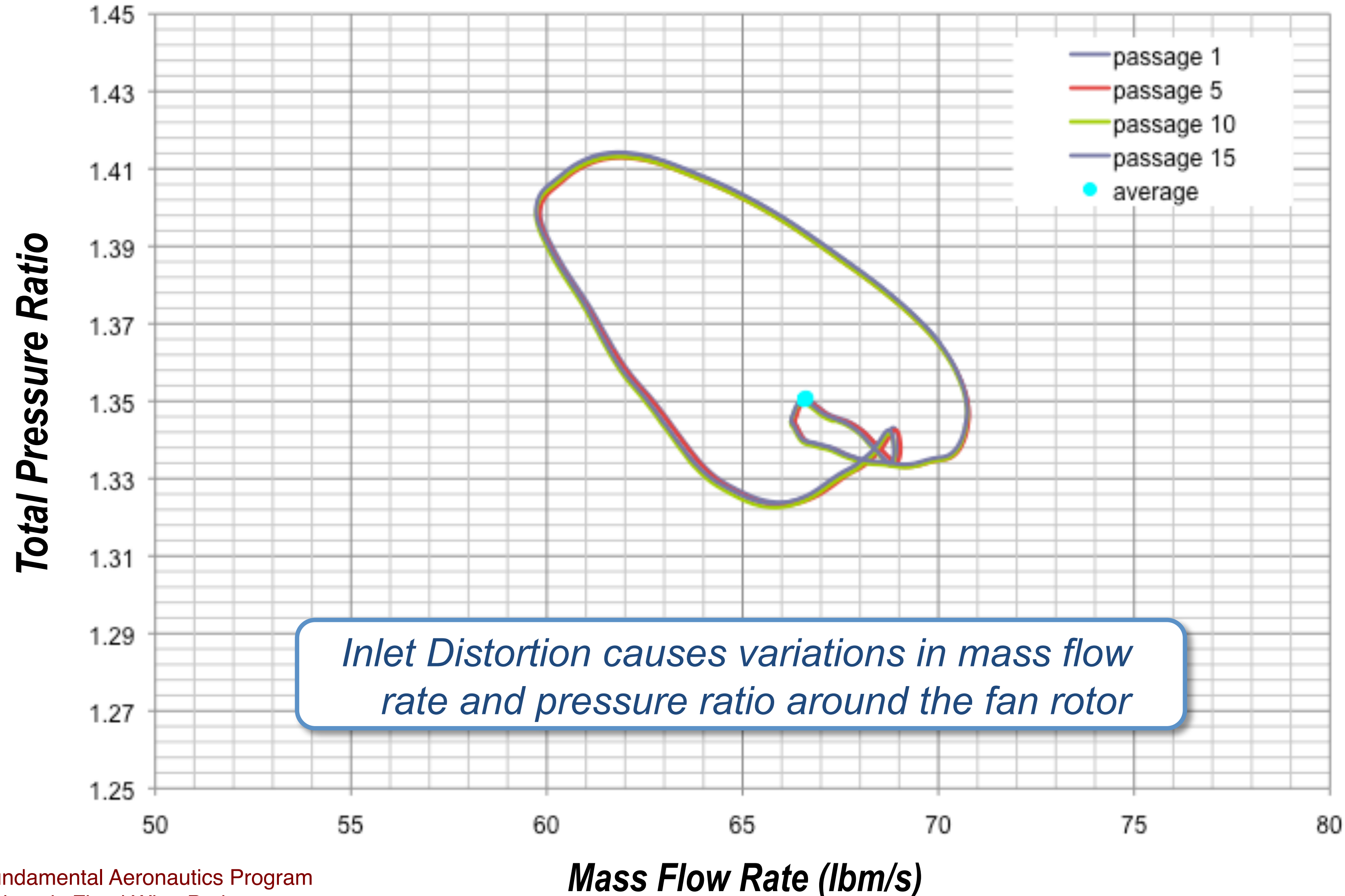


Aeroelastic Formulation

- Blade structural dynamics modal equations with aerodynamic load

$$[M]\{\ddot{q}\}+[K]\{q\}=\{AD\}$$

$\{AD\}$ is the motion-independent aerodynamic load vector – ***Modal Force***

$$AD_i = \int \vec{\delta}_i \cdot p\, d\vec{A}$$

Modal Force *computation requires* ***unsteady pressure*** *and* ***modal displacements***

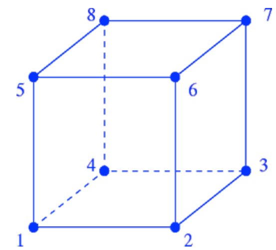
$$\{q\}=\left[[K]-\omega^2[M]\right]^{-1}\{AD\}$$

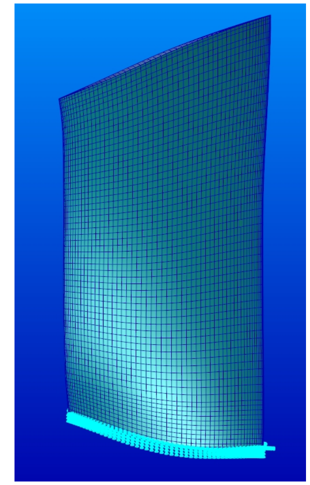
Forced Response

Structural Dynamics Model & Results

Blade structural model created based on aero design iteration (structural design is in progress)

- 8-node brick elements
- 9,782 elements, 15,096 nodes
- 222 nodes at the root constrained



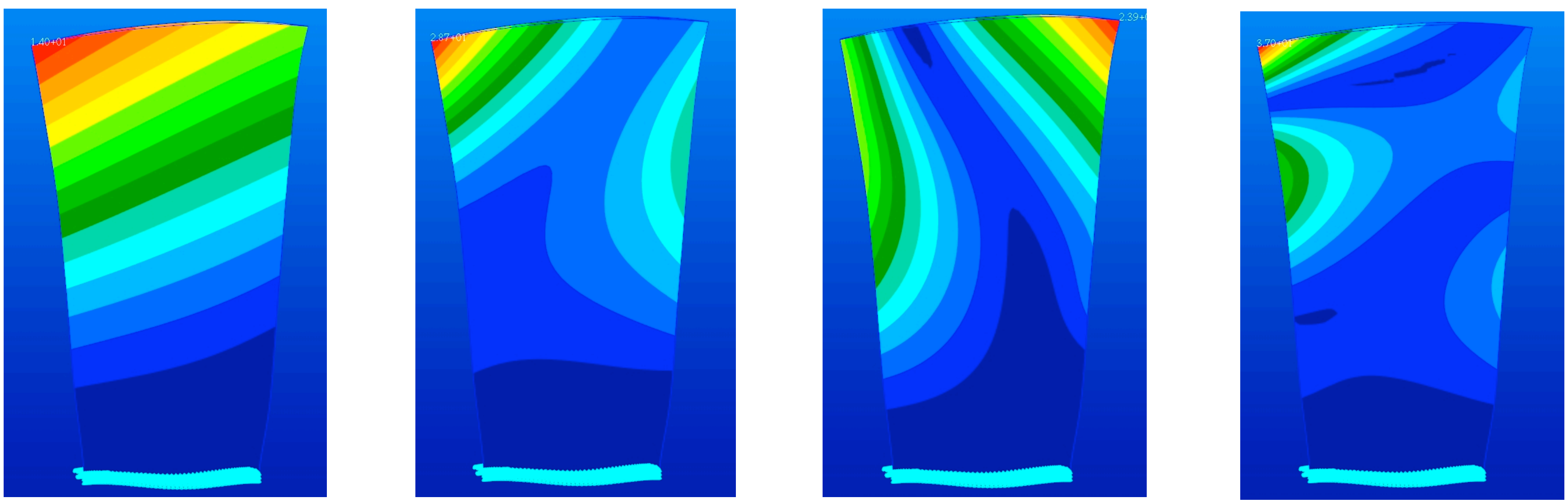


mode 1
63.5 Hz

mode 2
156.6 Hz

mode 3
224.8 Hz

mode 4
346.6 Hz

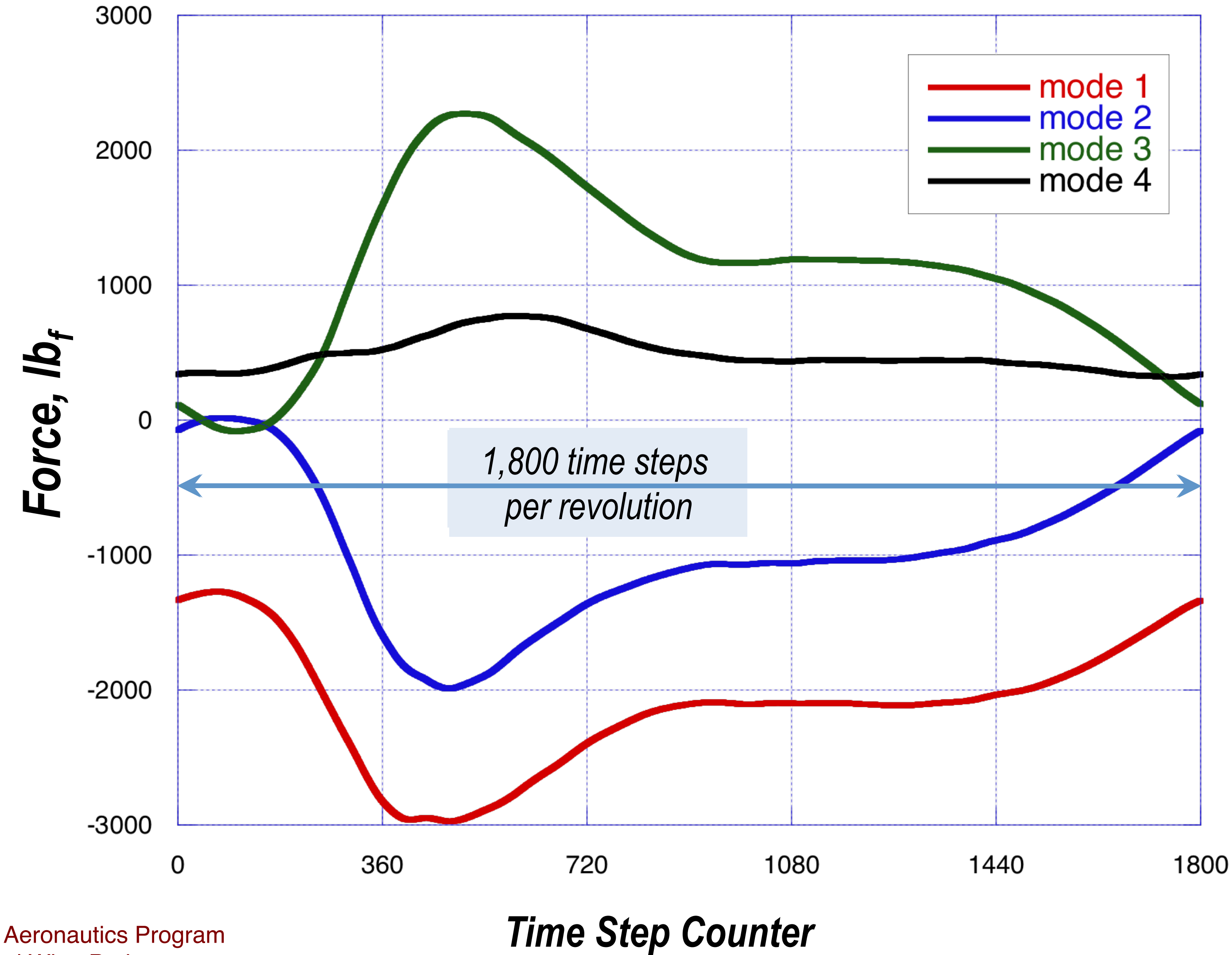


Blade Vibration Modes or Modal Displacements

Modal Force

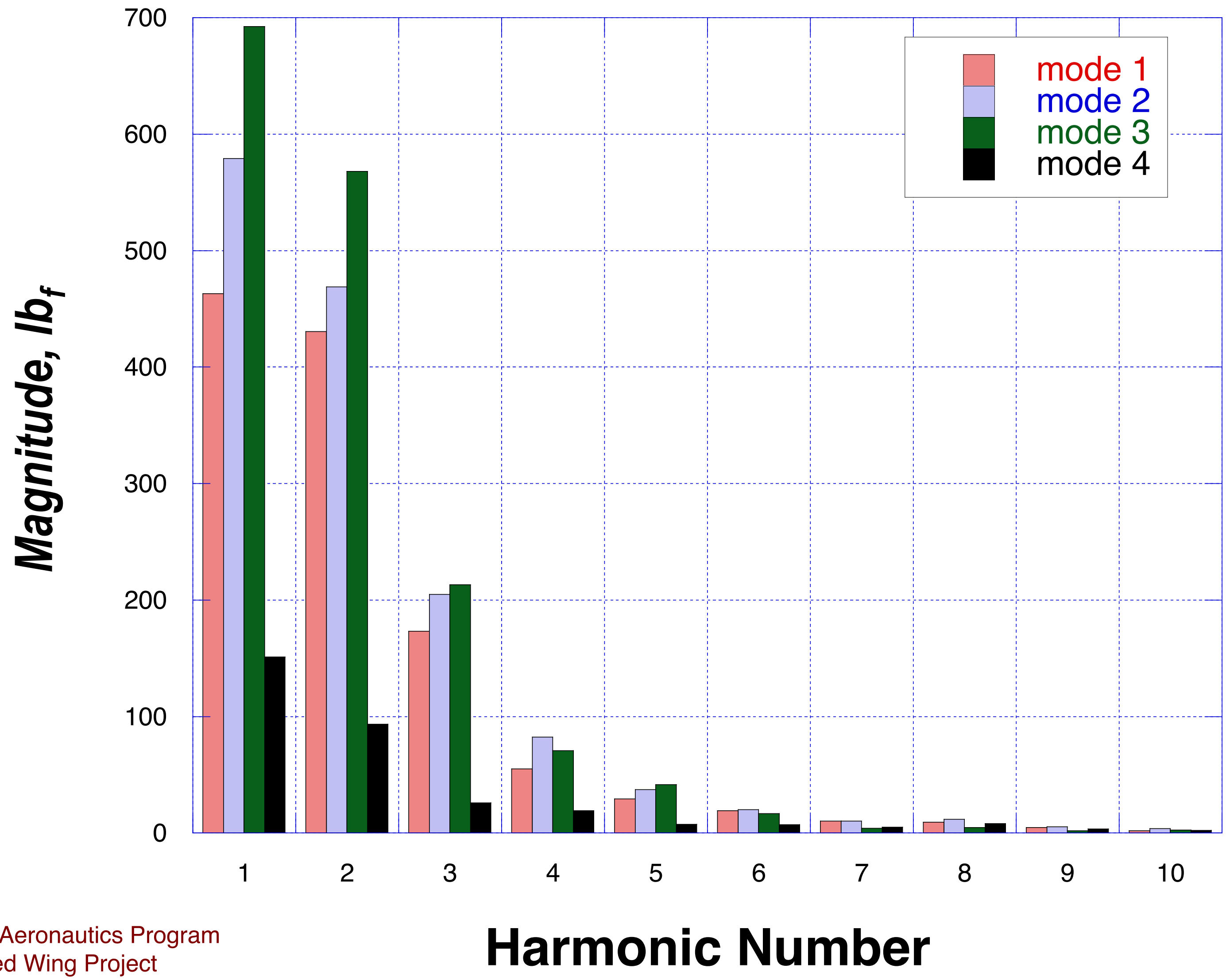
Time history over one rotor revolution

$$AD_i = \int \vec{\delta}_i \cdot p\,d\vec{A}$$

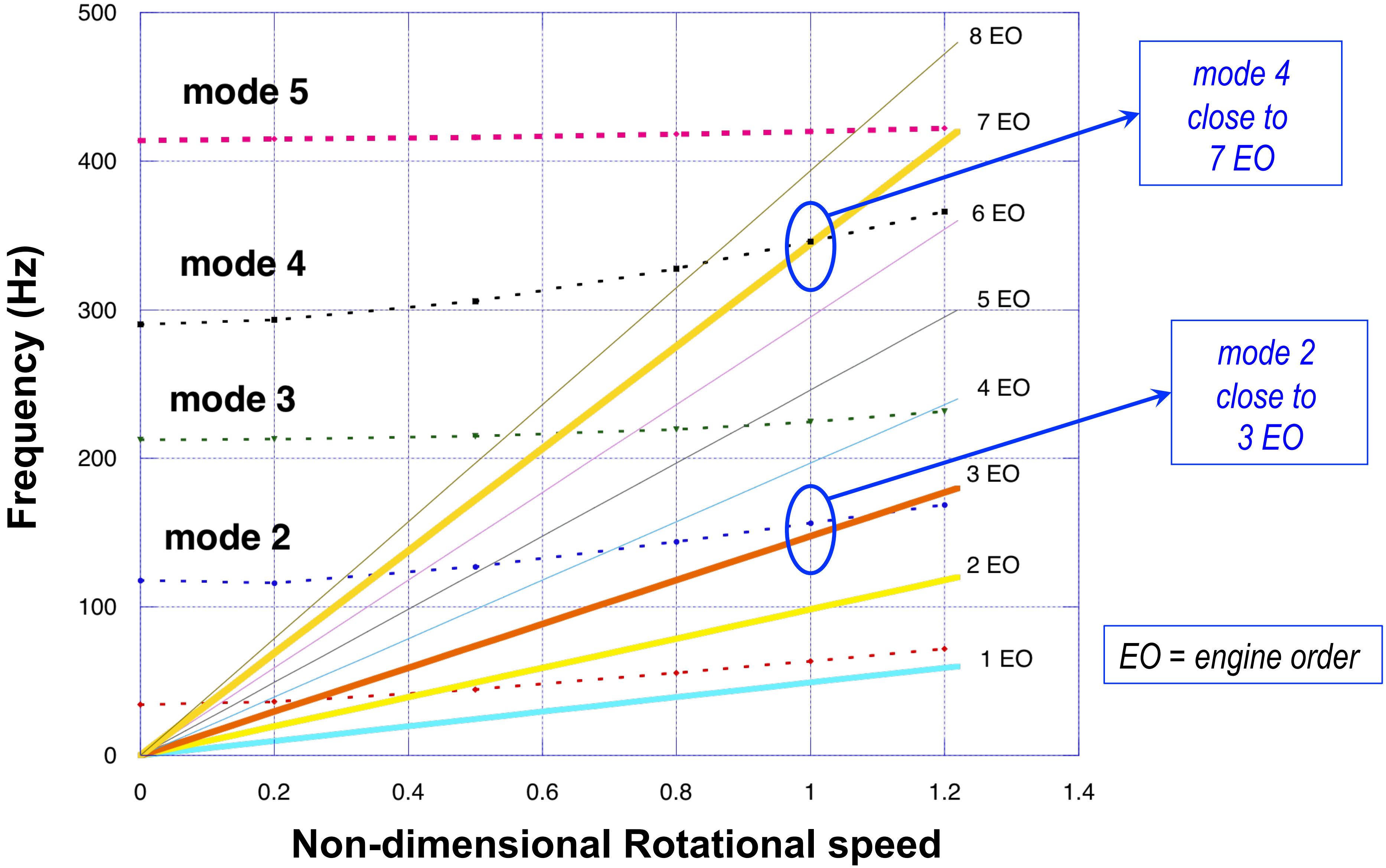


Modal Force

Fourier components

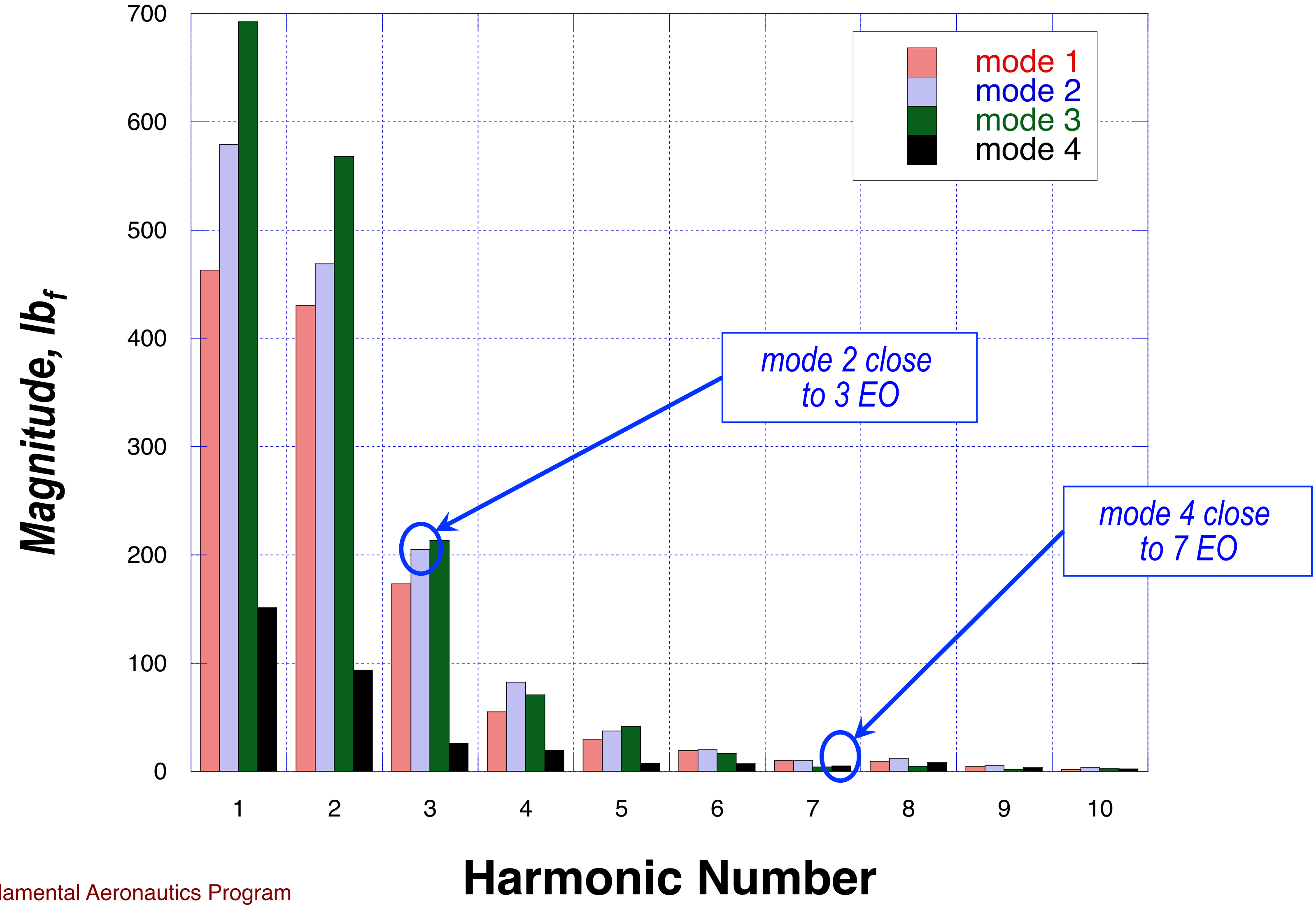


Campbell Diagram



Modal Force

Fourier components

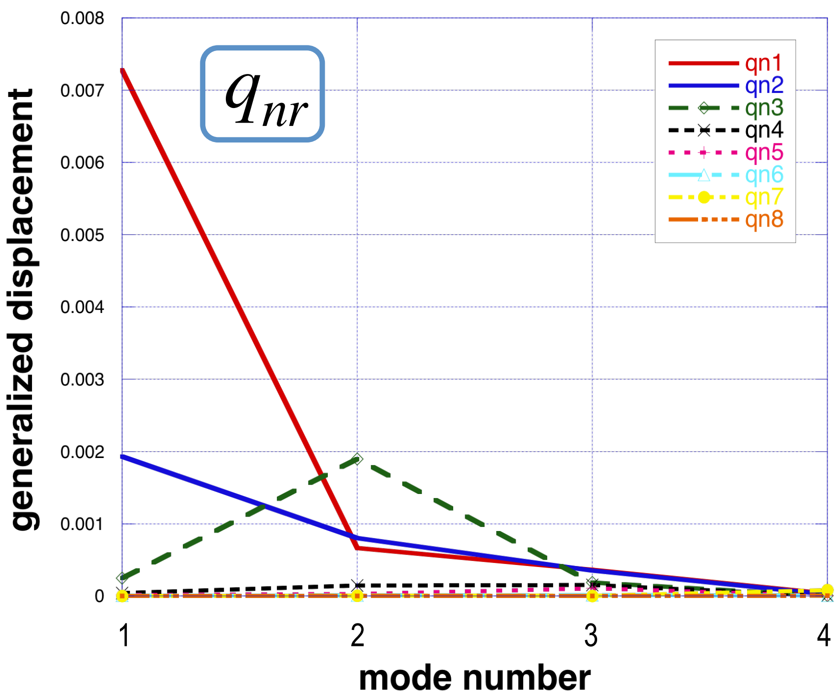


Forced Response – Vibration Amplitude and Dynamic Stresses

- Dynamic stresses are required to determine fatigue characteristics (Goodman diagram)

$$\{q_{nr}\} = \left[[K_n] - \omega_r^2[M_n]\right]^{-1}\{AD_{nr}\}$$ *for n^{th} mode, r^{th} harmonic*

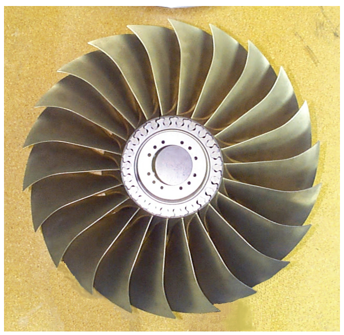
dynamic stress $\sigma_r = \sum_n s_n q_{nr}$ *where s_n is the modal stress*



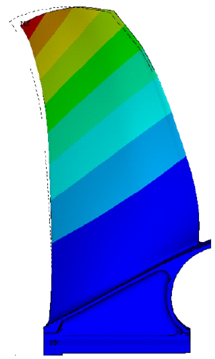
harmonic or engine order	vibration amplitude (inch) at tip t.e.	dynamic stress amplitude (psi)
1	5.5×10^{-2}	273
2	3.0×10^{-2}	290
3	1.9×10^{-2}	$\boxed{666}$
4	3.1×10^{-3}	308
5	2.6×10^{-3}	169
6	2.7×10^{-4}	33
7	7.0×10^{-4}	$\boxed{427}$
8	6.0×10^{-5}	19

Flow Chart for Flutter Stability Computation

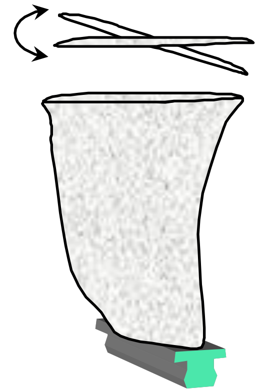
- Aerodynamic damping computation using TURBO-AE



Configuration

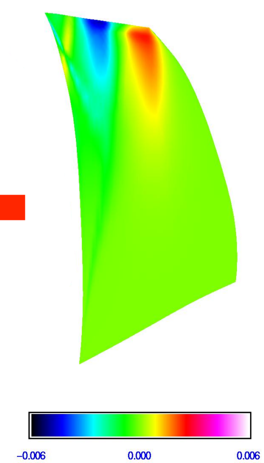


Mode Shape



Prescribe Blade Motion

$$\mathbf{X} = \mathbf{X}_0 \mathbf{e}^{\mathbf{i}(\omega t + \phi)}$$



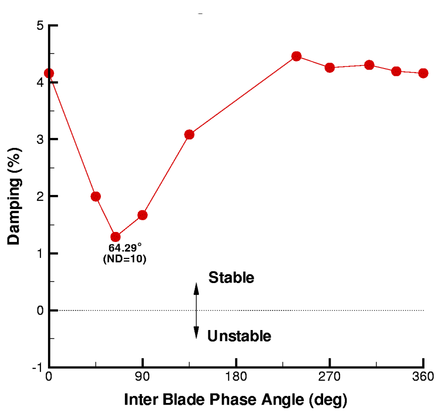
Calculate Work

(for all ω and ϕ of interest)

$$W = \oint \int_{surface} -p.d\vec{A} \bullet \left(\frac{\partial \vec{X}}{\partial t}\right) dt$$

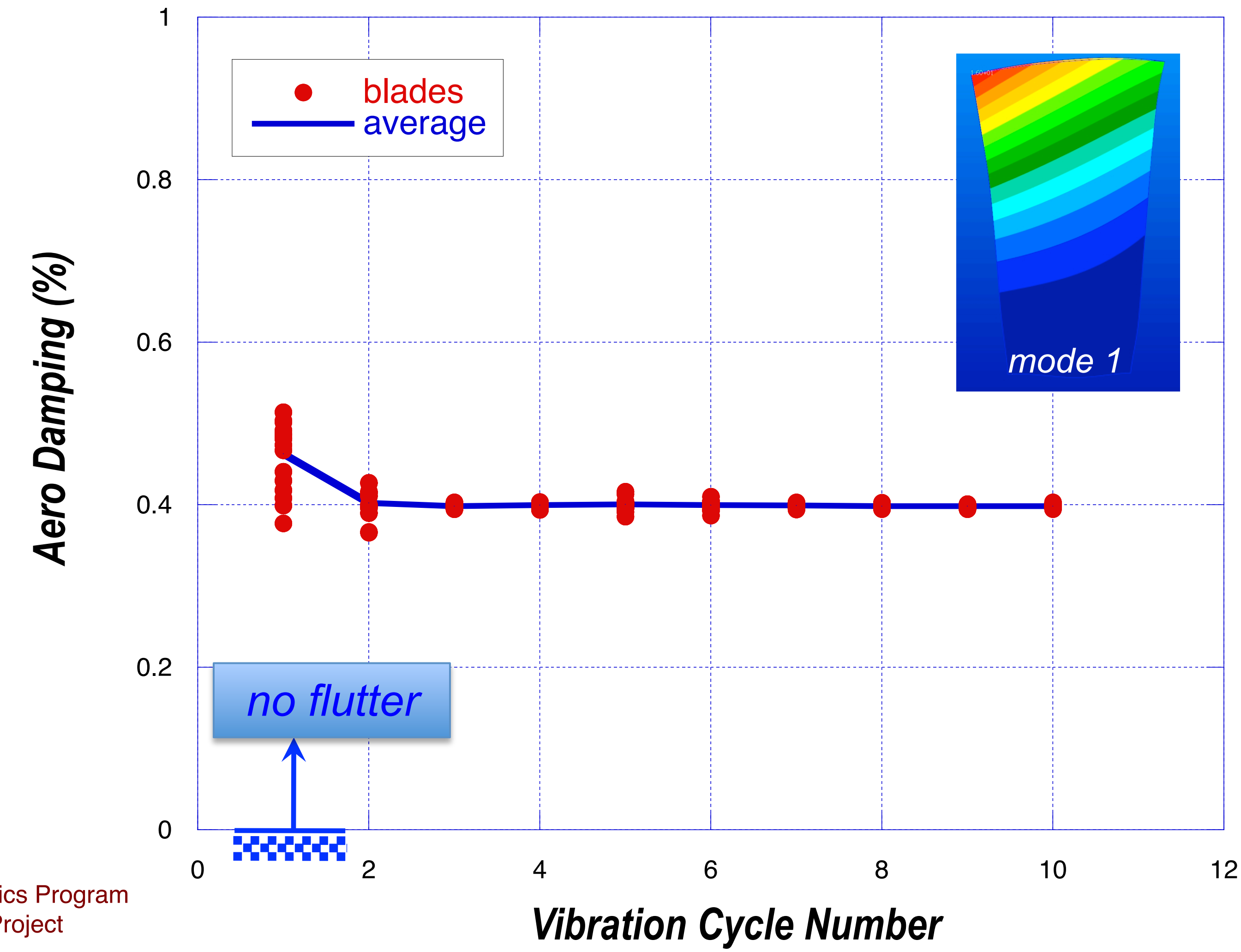
Calculate Aerodynamic Damping

$$\gamma = -\frac{W}{8\pi K_E}$$



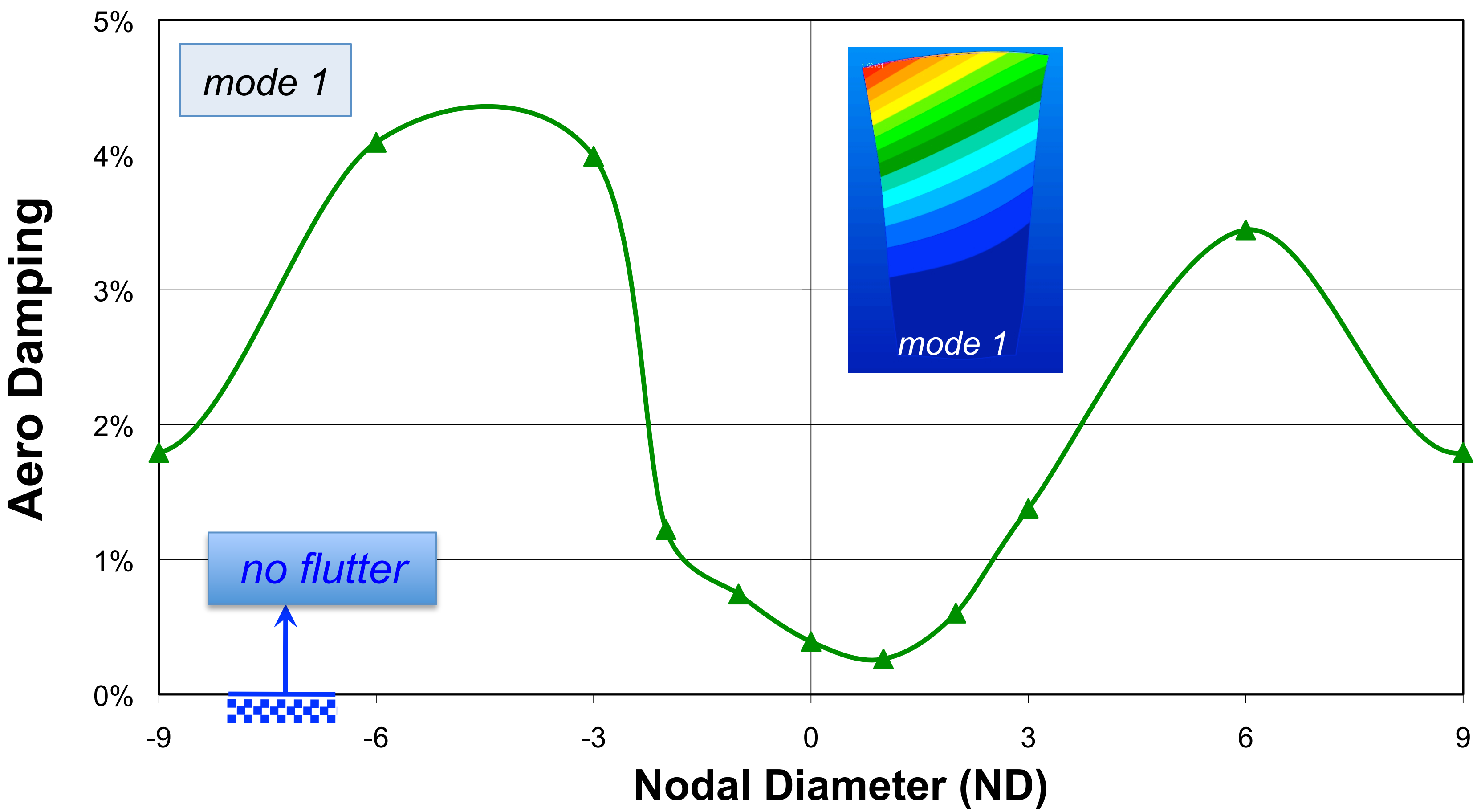
Flutter Stability with Clean Inflow

- Design operating speed, mode 1, 0 nodal diameter pattern (all blades in-phase), 18 blade passages (full rotor)



Flutter Stability with Clean Inflow

- Design operating speed, 18 blade passages (full rotor)
- Phase angle of vibration = 360 * Nodal Diameter / 18



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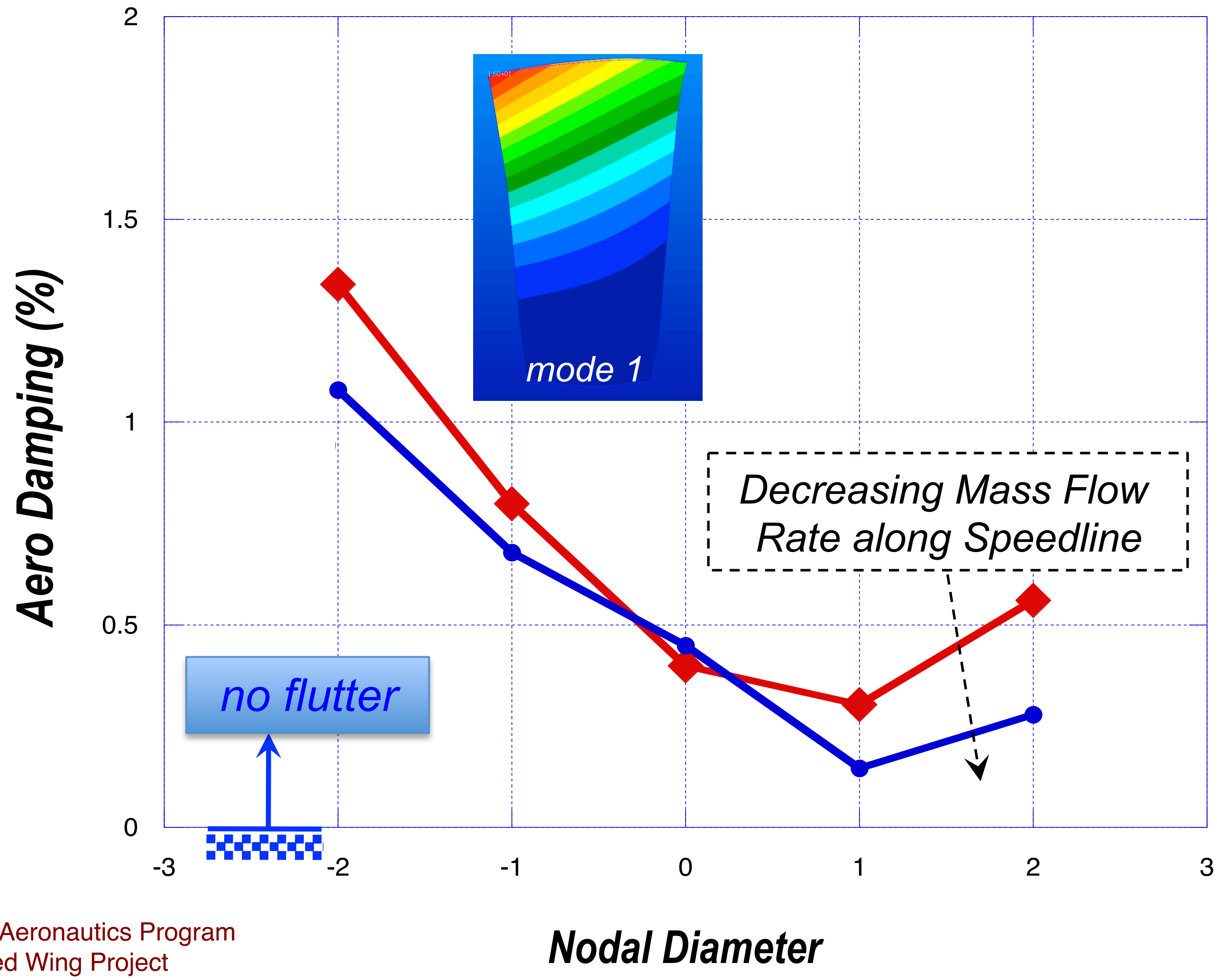

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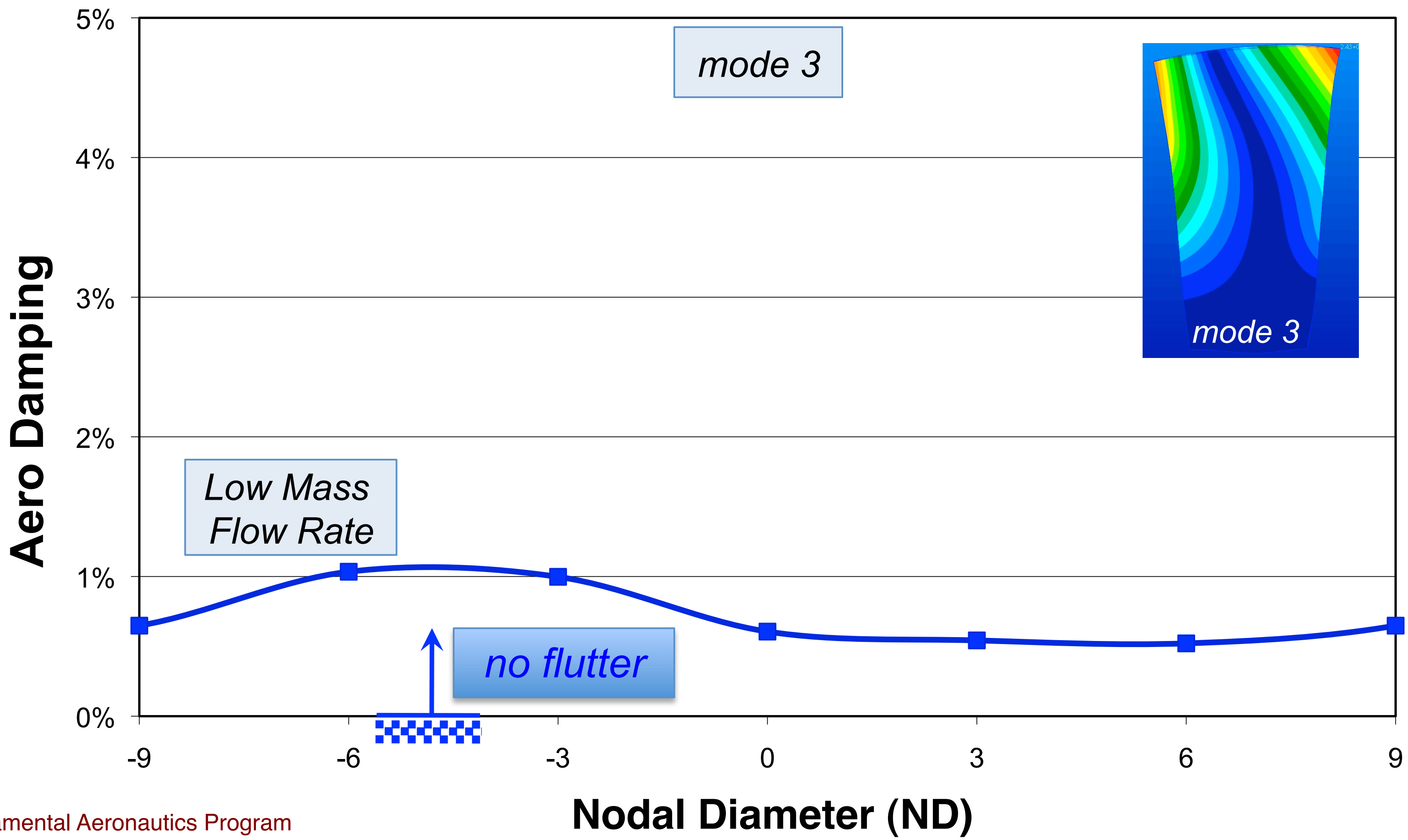


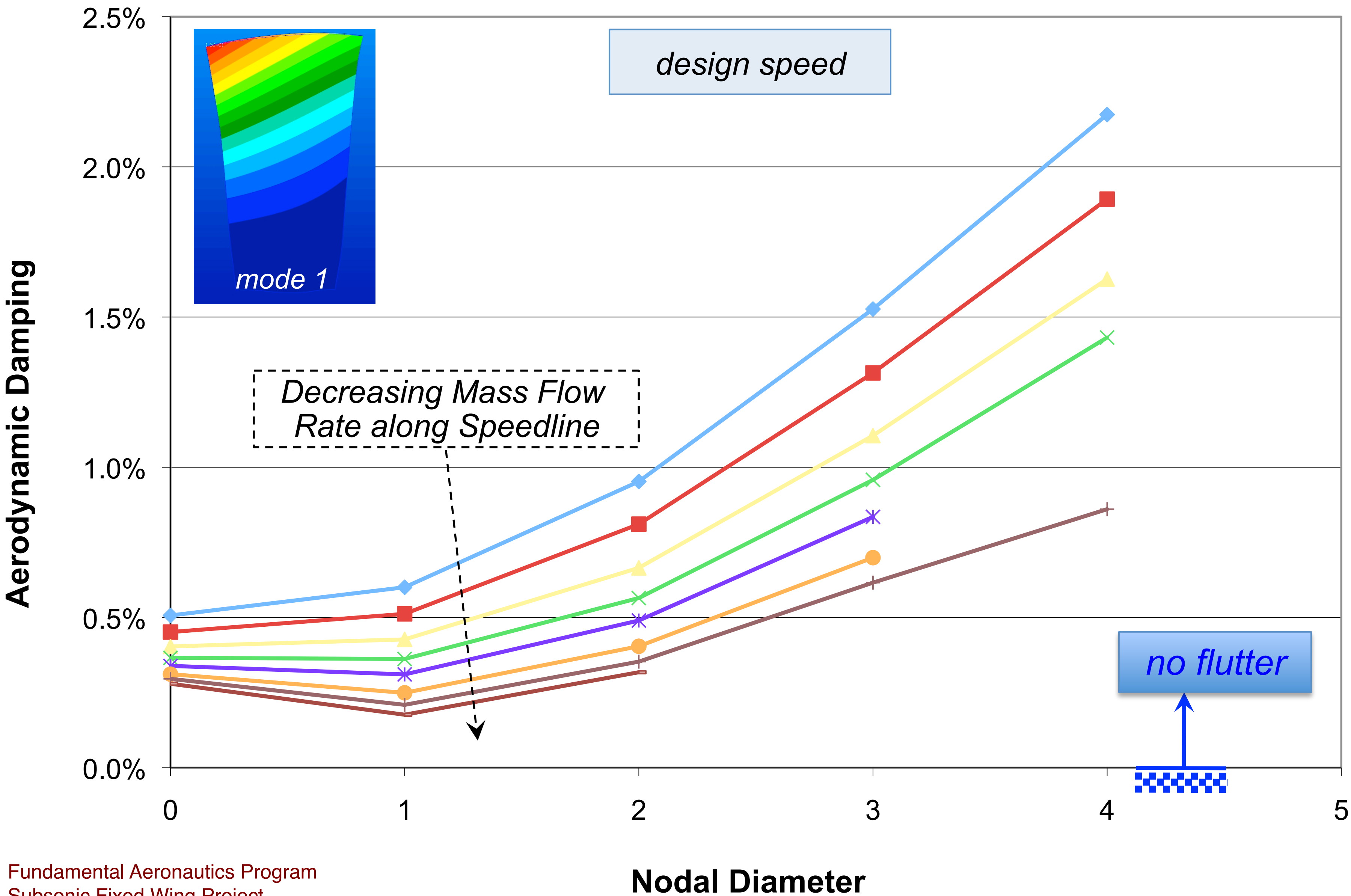
Fast-Running Aeroelastic Analysis

- Harmonic Balance CFD Method
- Fourier series expansion

  $$U(x,t) \approx \sum_{n=-N}^{N} \hat{U}_n(x) e^{jn\omega t}$$

  substituted into governing equations and solved for each harmonic component [Hall, 2000]
- Lax-Wendroff method
- 2nd and 4th order smoothing for stability
- Non-reflecting boundary conditions
- Spalart-Allmaras turbulence model
- Eigenvalue analysis to calculate aerodynamic damping

Harmonic Balance Results – Clean Inflow



Flutter Stability with Distorted Inflow

Various Approaches

- Circumferentially average the distorted inflow to obtain an equivalent radial profile; use work-per-cycle analysis
- Select a portion of the inlet distortion to represent a "worst-case" inflow condition that is used at all circumferential locations; use work-per-cycle analysis
- Prescribe blade vibrations and distorted inflow; use work-per-cycle analysis; average the results over all blades, and over multiple blade vibration cycles
- Use tightly-coupled aeroelastic analysis with distorted inflow; blade vibrations are determined as part of the computations; post-process time history to estimate average damping over all blades and multiple vibration cycles

Flutter Stability with Distorted Inflow

Current Preferred Approach

- Prescribe blade vibrations and distorted inflow
- Use work-per-cycle analysis
- Average the results over all blades, and over multiple blade vibration cycles

$$Work = \oint_{cycle} \int_{surface} -p.d\,\vec{A} \bullet \left(\frac{\partial \vec{X}}{\partial t}\right) dt$$

Unsteady pressure includes effect of

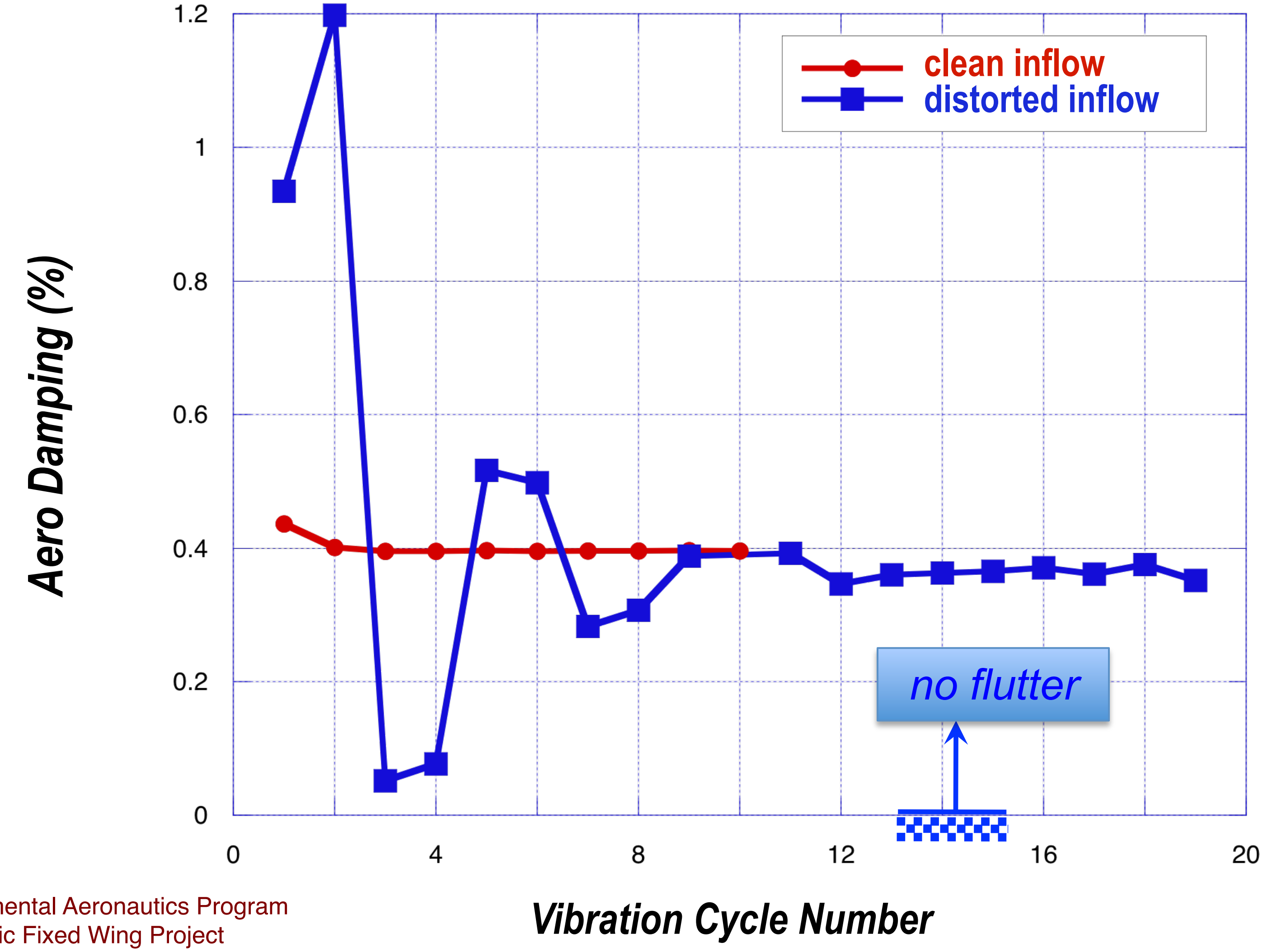
1) inlet distortion

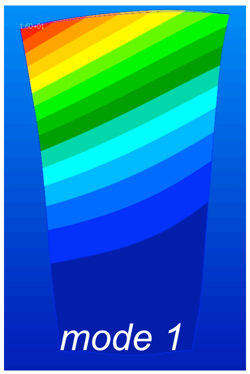
2) blade vibration

isolate this component to assess flutter stability

Flutter Stability with Distorted Inflow

- Design operating speed, mode 1, 0 nodal diameter pattern (all blades in-phase), 18 blade passages (full rotor)





Summary

- Created structural model based on aero design iteration and computed structural dynamics characteristics
- Performed aeromechanical analysis of design iteration
- Performed fan flutter analysis with clean inflow at design speed – no flutter encountered at conditions analyzed; additional work needed at part-speed conditions
- Performed distorted inflow analysis for forced response vibrations to determine dynamic stress at design speed – additional work needed at on-resonance conditions near design speed
- Performed initial analysis with blade vibrations and distorted inflow to estimate flutter stability – additional flutter analyses needed for other vibration modes and operating conditions

Future Work

- Extend computational domain to include fan exit guide vanes in the unsteady aerodynamics analysis
- Perform aeromechanical analysis on updated fan stage design with non-axi-symmetric exit guide vanes
- Perform aeromechanical analysis on final inlet-fan design to ensure safe wind-tunnel test

- Develop tightly-coupled aeroelastic analysis capability in TURBO for more detailed analysis of blade vibrations with distorted inflow
- Develop inlet-fan coupled aeroelastic analysis capability

NASA